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VISINTIN et al.

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Examiner: [to be assigned]

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Title: Method and Electromagnetic Sensor for  
Measuring Partial Discharges in Windings  
of Electrical Devices

**SUBMISSION OF CERTIFIED COPY OF APPLICATION IN SUPPORT OF A  
CLAIM FOR PRIORITY UNDER 35 U.S.C. § 119**

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Sir:

Applicant submits herewith a certified copy of the prior application identified below, in support of a claim for priority under 35 U.S.C. § 119 in the above-identified patent application:

Country	Priority Document Appl. No.	Filing Date
DE	02405849.7	02 October 2002

Prompt acknowledgment of this claim and submission is respectfully requested.

Respectfully submitted,

Date: 24 JUNE 2004

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02405849.7

Der Präsident des Europäischen Patentamts;  
Im Auftrag

For the President of the European Patent Office

Le Président de l'Office européen des brevets  
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**R C van Dijk**





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Bezeichnung der Erfindung/Title of the invention/Titre de l'invention:  
(Falls die Bezeichnung der Erfindung nicht angegeben ist, siehe Beschreibung.  
If no title is shown please refer to the description.  
Si aucun titre n'est indiqué se référer à la description.)

Method and electromagnetic sensor for measuring partial discharges in windings of electrical

In Anspruch genommene Priorität(en) / Priority(ies) claimed / Priorité(s)  
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**Method and electromagnetic sensor for measuring partial discharges in  
windings of electrical devices**

5

**Technical Field**

The invention refers to a method and an electromagnetic sensor for measuring partial discharges (PD) in windings of electrical devices, e.g. electrical generators and motors, particularly in stators and/or rotors, stressed by voltage sources having high frequency (surge) components.

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**Related Prior Art**

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Methods and sensors for measuring partial discharges in windings of electrical devices, e.g. Ac or Dc electrical generators and motors, are already known in the prior art. These devices are generally fed by power networks at industrial frequencies of either 50 or 60 Hz. Currently both, couplers and electromagnetic sensors available on the market, are broadly used for partial discharge measurements. These measuring devices are either capacitors appropriately placed within the electric machine or outwardly. In addition, in some cases high frequency sensors are located in the stator slots.

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Partial discharges, that can lead to breakdowns in the insulating system, are caused by high internal stresses, mainly induced by 50 / 60 Hz voltages, as well as by high frequency electromagnetic fields due to lightning pulses, connection transients etc. Generally, these impulsive stresses are not uniformly distributed along the stator winding, but are located within the first turns connected to the high-voltage source, so they can principally induce failures in the turn and / or conductor insulation of the winding, that may lead then to the ground insulation yielding. These damages induced by such impulsive stresses are even more

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severe if frequency converters are interposed between the electrical machine and the network, in particular if pulse width modulated (PWM) inverter fed motors are considered.

- 5 A discharge inception is generally bound to the characteristics of the dielectric materials and to the whole insulation system, as well as to the employed manufacturing technology. For measuring the turn and / or conductor insulation integrity and their limits, present off-line techniques apply voltage pulses to the winding by means of a so-called surge tester. These instruments compare the low  
10 frequency responses of two coils or two groups of coils belonging to the same winding. Often the applied surge voltages cause damages in some insulation areas owing to the low sensitivity of this technique. Therefore, relatively big pulses are needed that stress gratuitously the dielectric and accelerate in any case the aging. There are even more disadvantages in that method used up to now, as e.g.  
15 the need to induce a clear short-circuit, and the lack of measuring a value related to the condition of the turn or conductor insulation of the respective winding.

Campbell et al. describe in "Practical On-line Discharge Tests for Turbine Generators and Motors", IEEE Transactions on Energy Conversion, Vol. 9, No.2,  
20 June 1994, pp.281 –287, an on-line partial discharge test under 50 / 60 Hz stresses only using high voltage bus couplers or using stator slot couplers (SSC). The former consist of high voltage capacitors which are connected to the machine terminals, the latter are ultra wide band detectors installed under a few stator wedges closing the slots containing the stator bars. An instrument for converting  
25 the pulses from each coupler to digital form is part of the test arrangement. By means of differential measurements, noise signals coming from outside can be recognized.

Further, Stone et al. describe in "New Tools to Determine the Vulnerability of  
30 Stator Windings to Voltage Surges from IFDs", Proc. IEEE Electrical Conference, Cincinnati, October 1999, pp. 149-153, a partial discharge measuring system for measuring partial discharge pulses that occur during steep fronted voltage surges



from Inverter Fed Drives (IFDs). For this test arrangement, a device is used that attenuates the surge voltage more than 10000 times (80 db), while leaving the partial discharge pulses essentially unchanged.

5 Major drawbacks of the known measuring techniques are that they do not provide an absolute measurement, i.e. they only allow damage recognition by means of a comparative method and therefore can not be used if only one probe is available at a time. Further, the known measuring techniques provide only information on the presence of possible short-circuits in the turn/conductor insulation if the  
10 voltage level during the test is high enough to induce a clear short-circuit. Another important drawback is the fact that the present measuring techniques can only be used during production, as a quality test, but give only passed/non-passed type results. This does not provide any parametric indication, e.g. a value of the turn/conductor insulation condition, on which an assessment of further actions to  
15 improve the winding insulation can be based. Consequently, the present measuring techniques may require relatively high voltage pulses which may induce insulation damages not present before the test and in general will cause accelerated aging of the insulation. Further, the present measuring techniques do not provide any indication about incipient damages or the general condition of the  
20 turn/conductor insulation. Finally, the presently known methods do not provide any means to locate the damage because the short-circuits can only be clearly seen if the surge tester power is high enough to "burn" the insulation surrounding the discharge site.

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### Disclosure of the Invention

Therefore, it is an object of the present invention to provide an improved measuring method, which avoids the stated drawbacks of the prior art. The  
30 improved measuring method should provide more information about the status of the insulation system by using non-destructive techniques. If a surge voltage is applied it should be similar or even lower than the actual operation voltage of the

electric machine. Clear short-circuits should be avoided. The sensor equipment should be simple, available in a greater number and at reasonable costs.

5 This object is solved by a method for measuring partial discharges in windings of electrical devices having the features of claim 1 and an electromagnetic sensor for measuring partial discharges in windings of electrical devices having the features of claim 11. Preferred embodiments of the present invention are described in the dependent claims.

10 The present invention provides an improved measuring method which avoids the drawbacks of the prior art and which provides more detailed information about the status of the insulation system by using non-destructive techniques. Clear short-circuits during testing are not necessary any more. The electromagnetic sensor according to the present invention is surprisingly simple, available in a greater  
15 number and at reasonable costs.

The method for measuring partial discharges in windings of electrical devices according to the present invention is comprised of the following steps:

- Applying voltage having high frequency (surge) components to the winding of the  
20 electrical device;
- Detecting partial discharge signals by means of a tuned VHF and/or UHF electromagnetic sensor located close to the electrical device; and
- Evaluating the detected sensor signals by means of electrical hardware or software.

25

The present invention comprises a method for measuring partial discharges for example in stator windings of electrical machines which uses VHF and/or UHF electromagnetic couplers, in particular in the GHz range, for measuring the discharge signals and for attenuating unimportant signals. By means of the  
30 proposed technique the partial discharge inception voltage can be measured under surge voltage stresses and at the same time all the general characteristics of the discharge patterns can be obtained, e.g. their distribution or the highest

discharge patterns. Indeed, the inception and/or extinction voltage is an important parameter, which allows an evaluation of the quality of the insulation system. The detected inception voltage can then be compared to the highest levels of the surge voltages that can be present during the machine service; the levels can be either  
5 measured in actual conditions or computed. The measurement is performed without any electrical connection between the sensor and the sample under test, thus being a safe procedure. The measurement can be run during the manufacturing process or in the quality control tests or during normal operation, when high frequency components are present in the voltage/current source (for  
10 example during frequency converter feedings).

A preferred embodiment of the method according to the present invention comprises that a suitable surge test pulse voltage is applied to the windings of the electrical device. However, as mentioned before, this is not an exclusive  
15 requirement since the measurement can also be executed under normal operation conditions with operation voltages having high frequency components, i.e. surges.

Another preferred embodiment of the method according to the present invention comprises that a plurality of sensors is used to determine the position of the  
20 discharge location. The first experimental results on motor windings showed that different signal shapes could be detected, depending on the distance between the sensor position and the discharge site. For example, the detection of an „unipolar“ discharge signal can infer that the discharge area is very near to the acquisition location, because the discharge is picked up before any signal reflection. On the  
25 contrary, an „oscillating“ signal can be considered as an indicator of a partial discharge located quite far away from the sensor site. Discharge locations may be simply retrieved if several sensors are used.

Further, a preferred embodiment of the method according to the present invention  
30 comprises that the applied voltage is a high frequency Ac or a Dc voltage or a frequency converter output. In the case of a Dc voltage, an induced surge pulse is preferable to gain best measurement results.

Still another preferred embodiment of the method according to the present invention comprises that a surge test voltage having a variable pulse is applied wherein the repetition rates are different from 50/60 Hz. Thus, the test results can  
5 be clearly distinguished from power supply signals and test frequencies.

Another preferred embodiment of the method according to the present invention comprises that the detected sensor signals are filtered by a conditioning circuit. Alternatively the detected sensor signals are filtered by a software filter, e.g. based  
10 on the Fast Fourier Transformation (FFT). The discharge patterns can then be quantitatively analyzed through stochastic analyses.

Another preferred embodiment of the method according to the present invention comprises that the sensor is located near the coils connected to the high voltage  
15 source since this will generally provide the strongest signals.

Another preferred embodiment of the method according to the present invention comprises that at least two high frequency sensors are placed close to the machine's high voltage terminal and to the low voltage one respectively, to reject  
20 noise signals and / or to infer the discharge position along the winding by means of a differential measuring mode.

The proposed measuring methodology is considerably different from the techniques presently used in case of surge voltages. In particular, the use of very  
25 high-frequency electromagnetic couplers is now proposed, in order to measure the discharge signals, as well as to attenuate those unimportant as much as possible. The signals associated to partial discharges are known to have less than 10 ns rise times, whereas for example the pulse trains sent by pulse width modulated inverters generally have hundreds of nanoseconds (ns) rise times, if measured at  
30 the electric machine terminals. Therefore, to discriminate efficaciously the discharge signals from those induced by the surge testers, the coupling sensor has frequency characteristics capable of attenuating the latter, keeping unaltered

the former, or at least as much as possible. If pulse-width-modulation-like voltages are used, it has been experimentally proven that the sensor meets such requirements, if it has a bandwidth centered around some GHz. By applying the measurement method according to the present invention, a good discrimination  
5 can be obtained between discharge signals and those induced by the feeding itself. Other frequency ranges may be necessary if partial discharge measurements are to be carried out using different voltage shapes. Furthermore, this approach also allows the detection of partial discharges that happen during the rise front of the test pulse.

10

Only the discharge signals can finally be obtained if a proper conditioning circuitry is used, that further filters the measured pulses, thus attenuating the test pulse. Otherwise such a signal conditioning can be obtained by means of dedicated software, based for example on the Fast Fourier Transform (FFT), capable of  
15 pointing out only the frequency components related to the discharge signal. Whatever conditioning is chosen, the discharge signals can be processed afterwards, so as to study the amplitude distribution patterns, for example, by means of electronic equipment already developed and available on the market. This post-processing feature seems to be quite necessary in such measurements  
20 because the test voltage is generally slightly above the inception level only, thus the discharge does not happen at every pulse. In such conditions, acquisition time intervals should be relatively large, if compared to the duration of each pulse, to show the presence of partial discharge phenomena. Therefore a stochastic analysis seems to be necessary to characterize the discharge patterns both  
25 quantitatively and qualitatively. The statistic feature of the partial discharge events is further enhanced, whether possible surge test variations take place, and must be taken into account, due to the unsteadiness of the generated surges at the machine's terminals.

30

An antenna obtained from a coaxial cable (for example a BNC cable) is provided as VHF and / or UHF electromagnetic sensor for measuring partial discharges in windings of electrical devices according to the present invention.

In a preferred embodiment of the electromagnetic sensor according to the present invention the tuned frequency of the antenna is selected according to the signal range of interest, in particular in the GHz range. To that purpose the inner  
5 conductor of the coaxial cable piece is laid free in a length of  $\frac{1}{4}$  wavelength according to the frequency or frequency band wished to receive. The outer conductor can also be laid free.

In still another advantageous embodiment of the electromagnetic sensor,  
10 according to the present invention, the length of the antenna is 25 mm for a tuned frequency of 3 GHz. This is a typical application of the present invention, however the given values can vary from case to case.

Considering the frequency range involved, the proposed sensor is very selective  
15 which means that partial discharges can be detected only if they are located close to the sensor. As a consequence, these antennae are to be located where the discharge probability is relatively high, i.e. near the coils heavily stressed by electric fields, in other words near to those connected to the high voltage source. Indeed, this is not a restriction, due to the low cost of the antenna. Many of such  
20 sensors could be simply employed during any measurement, which also has the effect that the position of the discharge can be inferred rather exactly.

The possible discharge sites are the ground insulation and the inter-turn insulation, both in the slot area and in the end-winding region. If randomly wound motors are  
25 under consideration, for example vacuum pressure impregnated ones (VPI), it can be pointed out that a good resin refilling is usually reached in the slots, obtaining in such an area a low partial discharge inception probability, provided that the manufacturing process is properly carried out. On the contrary, especially in case of the vacuum pressure impregnated machines, the end-winding conditions are  
30 more uncertain due to air gaps between the coil turns which may lead locally to very high voltage gradients. As a matter of fact, the experience shows that surge voltages induce, in many cases, breakdowns exactly in the winding overhangs

where, in addition to some boundary effects of the electric field, the manufacturing process may lead to some resin lacks within the coils and causes some local damage of the insulation of the turns due to coil settlement in the stator and their mechanical adaptation.

5

### **Brief Description of the Drawings**

Following, the present invention will be described in further detail in connection  
10 with the attached drawings, wherein

Fig. 1 shows a schematic view of an antenna sensor according to a preferred  
embodiment of the present invention;

15 Fig. 2 shows an output signal of the antenna sensor according to figure 1 when  
placed near the first coil of a cross wire stator winding in a random wound  
motor;

Fig. 3 shows a surge test voltage when applied between the motor terminal of one  
20 phase;

Fig. 4 shows a partial discharge signal waveform obtained by an antenna sensor;  
and

25 Fig. 5 shows a surge test voltage and the output signal from the antenna sensor  
according to figure 1.

### **Preferred Embodiments**

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One preferred embodiment of the electromagnetic sensor according to the present invention is schematically shown in figure 1. According to this embodiment, the

electromagnetic sensor is obtained from an usual BNC coaxial cable, the latter consists of an inner conductor which is surrounded by a polyethylene dielectric which is entirely surrounded by a sheath material. The sheath material is surrounded by an outer conductor and coated with a (non shown) tube material, e.g. polyvinylchloride. To get the electromagnetic sensor according to the preferred embodiment of the present invention, as sketched in Fig. 1, the inner conductor is freed for a defined length  $l$  and the outer conductor can be cut off or simply turned inside out and stuck on the protective tube of the BNC cable. The free length of the inner conductor is directly related to the tuned frequency to be measured and can be calculated according to the formula:

$$l = \lambda/4.$$

wherein  $l$  = length of the freed inner conductor and  $\lambda$  = wavelength of the tuned frequency to be measured.

It has been experimentally proven that an antenna sensor, obtained from a simple coaxial cable as shown in figure 1, is suitable to be used as a very high frequency electromagnetic coupler. This antenna sensor can be produced at low costs and in a large quantity.

Figure 2 shows the signal that has been picked up with the proposed sensor from a random wound motor winding. In the diagram of figure 2, the following units are shown: X-axis time in  $\mu s$ , Y-axis Voltage in V. The antenna of figure 1 has been used as electromagnetic sensor. The antenna has been located near the first coil of a cross wire stator winding in a random wound motor, stressed by a steep fronted pulse. The antenna was 25 mm long for a tuned frequency of 3 GHz. The impulsive source produced a signal which reflects a damped vibration wave having an amplitude of 0,2 V, while the partial discharge induced a superimposed higher frequency signal, whose amplitude was 0,8 V, much bigger than the damped signal due to the impulsive source, so the discharge signal could be simply recognized.



Figure 3 shows the surge test voltage applied between the motor terminal of one phase (curve C). In the diagram of figure 3 the following units are shown: X-axis 500 ns/div; Y-axis 500 V/div. In this example the surge voltage had a rise time of approximately 700 Nano Seconds (ns). This waveform could be simply obtained through a differential measuring mode, by means of two wide frequency-band high voltage probes connected respectively to the motor high voltage terminal (curve A), and to the low voltage one (curve B).

Figure 4 shows a partial discharge signal waveform obtained by an antenna sensor according to the embodiment of figure 1. The antenna sensor has been located close to the first coil of a cross wire stator winding in a random wound electrical motor. In the diagram of figure 4 the following units are shown: X-axis 10 ns/div; Y-axis 20 mV/div. In Fig.4 the partial discharge signal waveform is shown, which has been detected by the antenna sensor, feeding a digital oscilloscope with a sampling rate of 1 GS/s. The proposed sensor antenna is capable of singling out discharges, even during the steep front of the test voltage, if properly designed, as shown in Figure 5.

Figure 5 shows in one diagram the applied impulse test voltage (curve A) together with the signal (curve B) picked up by means of the sensor of figure 1. In the diagram of figure 5 the following units are shown: X-axis 500 ns/div; Y-axis (curve A) 500 V/div, Y-axis (curve B) 20 mV/div. If signal B is considered, it can be clearly remarked a first high frequency signal, superimposed on the relatively low frequency component due to the impulsive feeding. This high frequency signal is related to a discharge event that happened during the rise time of the surge voltage. Afterwards, other discharges can be pointed out. Therefore this technique allows the recognition of the partial discharge inception voltage simply by looking at the surge voltage level corresponding to the first detected discharge signal.



### Claims

1. Method for measuring partial discharges in windings of electrical devices, the method comprising the following steps:
  - Applying voltages having high frequency components to the winding of the electrical device;
  - Detecting partial discharge signals by means of a tuned VHF and/or UHF electromagnetic sensor located close to the electrical device and
  - Evaluating the detected sensor signals by means of electrical hardware or software.
2. Method for measuring partial discharges in windings of electrical devices according to claim 1, the method further comprising that a suitable surge test pulse voltage is applied to the windings of the electrical device.
3. Method for measuring partial discharges in windings of electrical devices according to one of the precedent claims, the method further comprising that a plurality of sensors are used to determine the position of the discharge location.
4. Method for measuring partial discharges in windings of electrical devices according to one of the precedent claims, the method further comprising that the applied voltage is a high frequency Ac or a Dc voltage or a frequency converter output.
5. Method for measuring partial discharges in windings of electrical devices according to one of the precedent claims, the method further comprising that a surge test voltage having a variable pulse is applied wherein the repetition rates are different from 50/60 Hz.

6. Method for measuring partial discharges in windings of electrical devices according to one of the precedent claims, the method further comprising that the detected sensor signals are filtered by a conditioning circuit.
- 5 7. Method for measuring partial discharges in windings of electrical devices according to one of the claims 1 to 5, the method further comprising that the detected sensor signals are filtered by a software filter, in particular based on the Fast Fourier Transformation (FFT).
- 10 8. Method for measuring partial discharges in windings of electrical devices according to one of the precedent claims, the method further comprising that the discharge patterns are quantitatively characterized by means of stochastic analysis.
- 15 9. Method for measuring partial discharges in windings of electrical devices according to one of the precedent claims, the method further comprising that the sensor is located near the coils connected to the high voltage source.
- 20 10. Method for measuring partial discharges in windings of electrical devices according to one of the precedent claims, the method further comprising that at least two high frequency sensors are placed near to the machine's high voltage terminal and to the low voltage terminal respectively, to reject noise and / or to infer the discharge position along the winding by means of  
25 a differential measuring mode.
11. Electromagnetic sensor for measuring partial discharges in windings of electrical devices wherein an antenna made of a coaxial cable is provided as VHF and/or UHF electromagnetic sensor.
- 30 12. Electromagnetic sensor for measuring partial discharges in windings of electrical devices according to claim 11, wherein the tuned frequency of the

antenna is selected according to the signal range of interest, in particular in the GHz range.

- 5       **13.**    Electromagnetic sensor for measuring partial discharges in windings of electrical devices according to one of claims 11 or 12, wherein the inner conductor of the coaxial cable is freed in a length of  $\frac{1}{4}$  wavelength corresponding to the tuned frequency to be detected.
- 10       **14.**    Electromagnetic sensor for measuring partial discharges in windings of electrical devices according to one of claims 11 to 13, wherein the length of the antenna is 25 mm for a tuned frequency of 3 GHz.



**Abstract**

A method for measuring partial discharges in windings of electrical devices comprised by the following steps: Applying voltages having high frequency components to the winding of the electrical device, detecting partial discharge signals by means of a tuned VHF and/or UHF electromagnetic sensor located close to the electrical device and evaluating the detected sensor signals by means of electrical hardware or software. Further, a VHF and/or UHF electromagnetic sensor for measuring partial discharges in windings of electrical devices is described wherein an antenna made of a coaxial cable is provided as electromagnetic sensor. The present invention provides an improved measuring method and sensor device, which avoid the drawbacks of the prior art. The improved measuring method provides more detailed information about the status of the insulation system and clear short-circuits during the testing are not necessary any more. The proposed sensor provides a surprisingly simple and inexpensive solution.

[Fig. 1]





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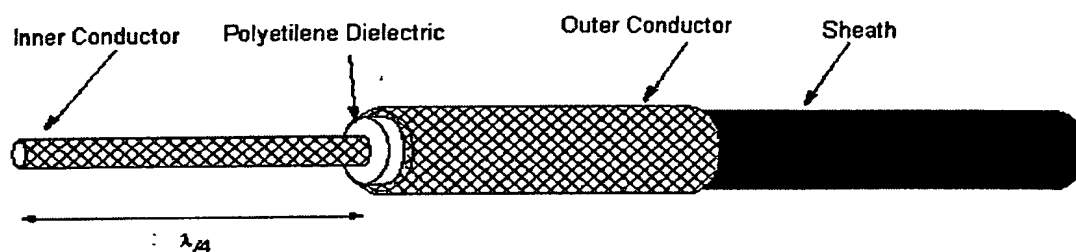


Fig.1

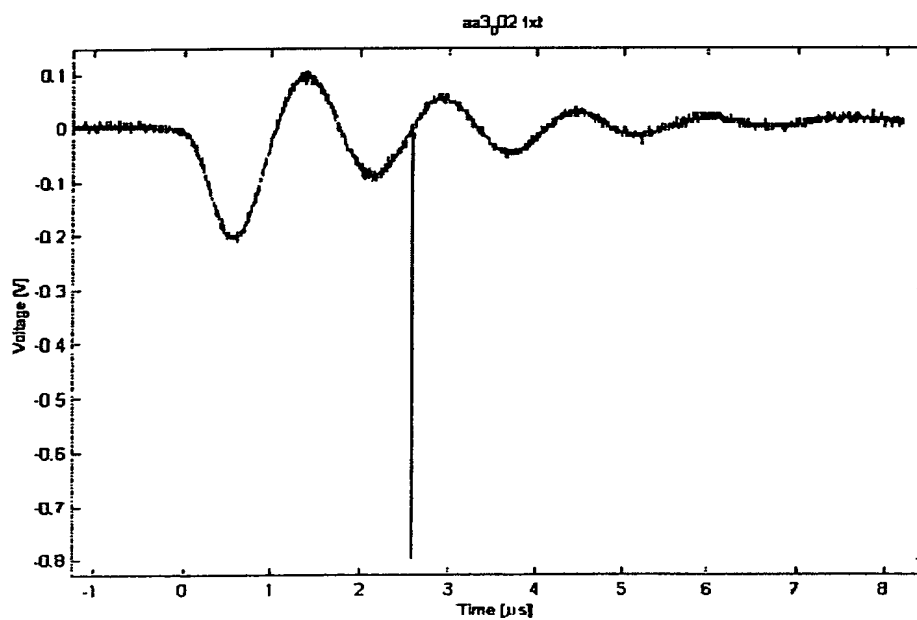


Fig.2

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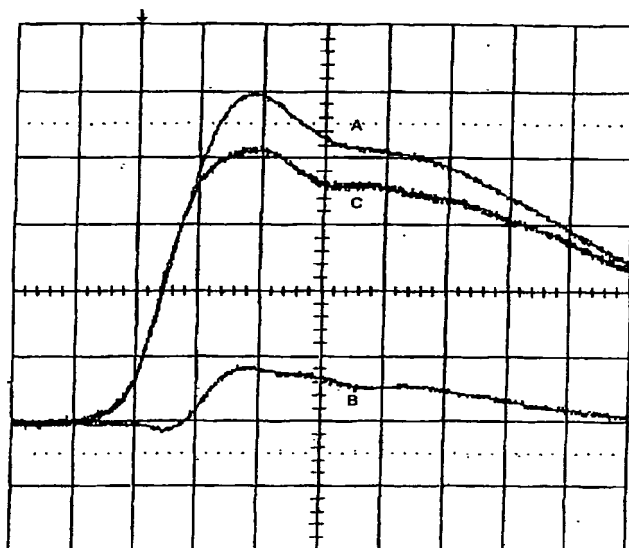


Fig.3

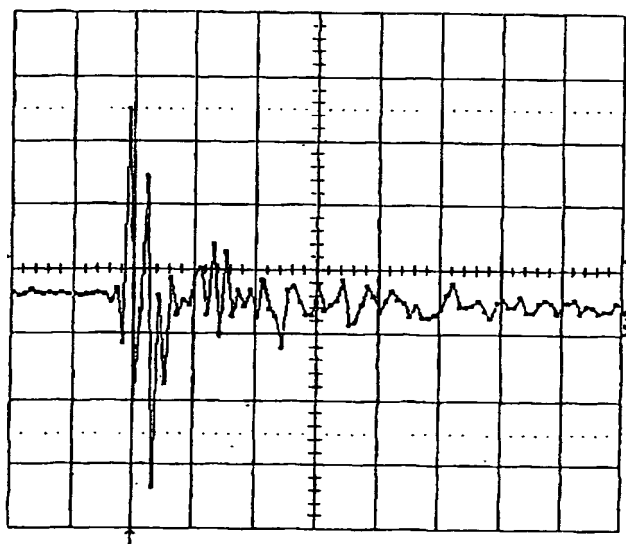


Fig.4

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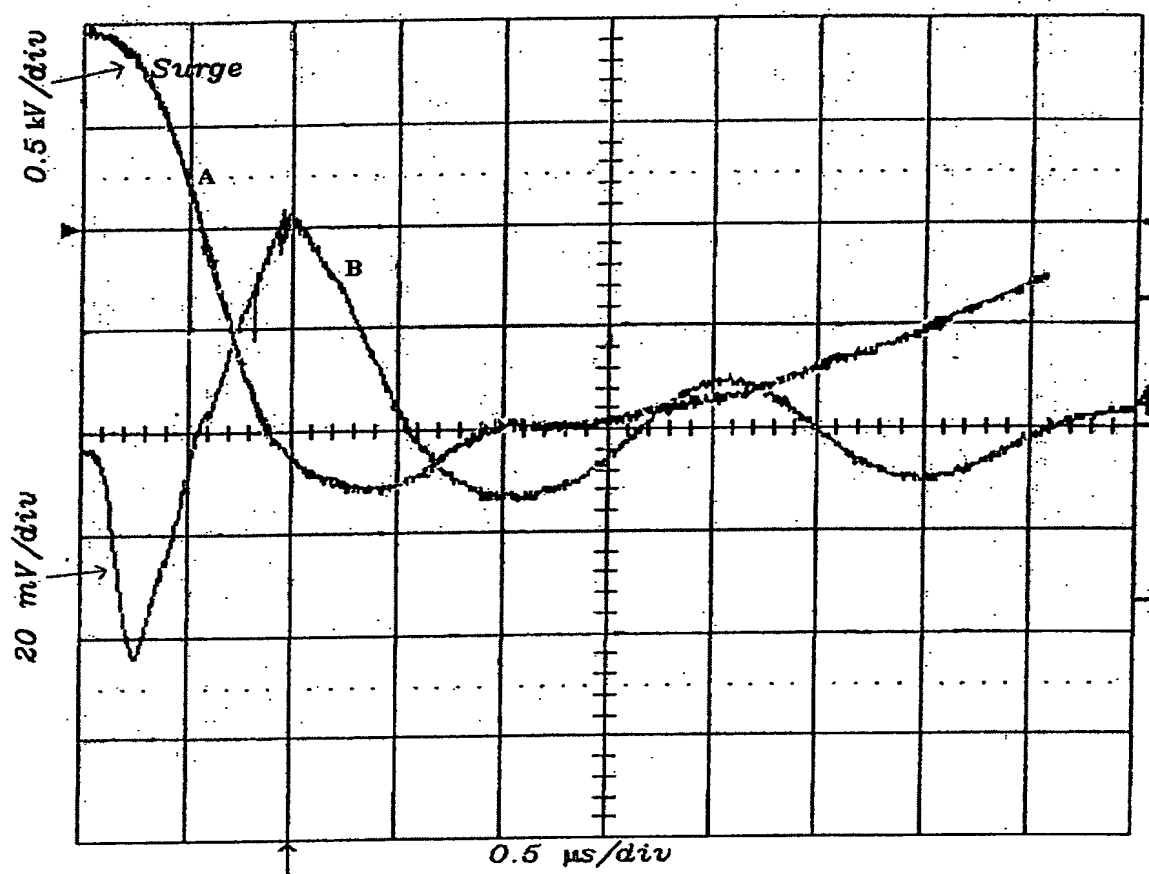


Fig.5

